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NAVIGATION OF PIONEER 12 DURING ATMOSPHERIC REENTRY AT VENUS

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The orbit of Pioneer 12 (PVO) decayed back into the atmosphere of Venus in the fall of 1992. This afforded a unique opportunity to investigate the Venusian cryosphere near the morning terminator by maintaining the altitude of periapsis in a corridor between 130 and 150 km above the surface. Navigation results were used by the mission operations team and also served as the primary data for the Orbiter Atmospheric Drag experiment (OAD). Aging solar cells on the spacecraft were expected to severely curtail power for scientific instrument operation and tracking coverage for navigation purposes. A technique was developed that could meet navigation requirements by optimizing the amount and placement of limited quantities of radiometric tracking data. The technique also allowed measurement of atmospheric drag a full order of magnitude lower than had previously been achieved with PVO. The PVO navigation team was able to adapt its operation to successfully meet changing requirements driven by the dynamic atmosphere and evolving physical condition of the spacecraft. This paper describes the PVO atmospheric reentry, the navigational strategy and operational scenario employed and the atmospheric drag measurements collected.

INTRODUCTION

The orbit of Pioneer 12 (PVO) decayed back into the atmosphere of Venus in the fall of 1992 due to solar gravitational perturbations. This afforded a unique opportunity to perform in–situ observations of the Venusian atmosphere. This was accomplished by maintaining the altitude of periapsis in a corridor between 130 and 150 km above the surface via a series of periapsis raise maneuvers. These maneuvers were performed until fuel was exhausted, and the spacecraft lost.

The Pioneer Venus Project is managed by the Ames Research Center. Reentry navigation support for the mission is provided to Ames by the Multi Mission Navigation Team of the Jet

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Propulsion laboratory (JPL)). Planning for the reentry was a coordinated effort of both groups. A number of adverse factors dominated the reentry operations and navigation strategy. Since the spacecraft has been in operations for almost 14 years, its solar cells had degraded and its batteries were failing. Before the reentry, it was anticipated that there would only be sufficient power for four hours of navigational tracking during each 24 hour orbit, and the remainder of time spent recharging the batteries. A data reduction technique was developed, in which limited amounts of tracking data were collected at strategically chosen points about the orbit, such that orbit determiuation accuracy was optimized. This technique also allowed measurement of atmospheric drag a full order of magnitude lower than had previously been achieved at Venus.

Navigation design for reentry was severely affected by the rapidly decaying orbit and the prescucc of a highly variable atmosphere. During each periapsis passage, the spacecraft experienced a significant velocity decrement duc to atmospheric drag, Trajectory prediction was uncertain, particularly because the variability of the nightside atmospheric density (50% one sigma). This mission marked the first usc of logarithmically interpolated atmospheric models for Venus, which greatly improved the accuracy of trajectory predictions.

Navigation results were used by the mission operations team and also served as the primary data for the Orbiter Atmospheric Drag experiment (OAD). Consequently, the navigation team was required to produce rapid solutions on a daily basis throughout reentry, to determine if maneuvers were needed to safeguard the spacecraft, and continually evaluate the validity of the atmosphere models used to plan and direct the reentry operation. The Principal investigator for the OAD was Dr.Gerry Keating of Langley Research Center.

This paper describes the PVO atmospheric reentry, the navigational strategy and operational scenario employed and the atmospheric drag measurements collected.

PVO REENTRY PROFILE

Pioneer Venus Program

PVO was placed into a highly eccentric, near polar orbit about Venus in early December, 1978. The mission's primary goals were the long term investigation of Venus, and its atmosphere (Ref. 1). Solar gravitational perturbations on the altitude of periapsis divide the mission into three phases. These phases are shown in Fig. 1. During the first phase, solar perturbations caused the altitude of periapsis to increase and onboard fuel was expended to maintain periapsis within the atmosphere. Emphasis was on the collection of atmosphere, ionosphere, altimetry and gravitational data. This phase occurred during solar maximum. The second phase of the mission began when fuel reserves ran low, and it became necessary to allow periapsis to rise, eventually reaching an altitude of about 2300 km in the summer of 1986, and then fall back toward the planet. This phase of the mission concentrated on the interaction of the solar wind with the upper atmosphere. In the third, or reentry phase, the remaining fuel was expended to again maintain periapsis within the sensible atmosphere. Measurements during the reentry phase complement those taken earlier in the mission because reentry occurred during solar minimum, and permitted observation of atmospheric response to the solar cycle. In addition, the latitude of periapsis had drifted from its initial 17° north to 10° south. Finally, in-situ measurements were extended to much lower altitudes than were made earlier, because greater risk duc to aerodynamic heating could be accepted at this point in the mission.

Physical Considerations

In addition to the secular evolution of altitude of periapsis described above, there is a short term reversal of the monotonic trend, referred to as an "S-Curve", duc to the characteristic shape of the periapsis altitude history, as seen in Fig. 2. This reversal occurs every 112 days when the orbit semi-major axis is perpendicular to the Venus-Sun line (i.e., when periapsis is over the terminator).

It is customary to discuss the atmosphere of Venus in terms of Local Solar Time (1,S'1'). LST is the Venus centered angle, expressed as 24 hr of time, of the position of the Sun as seen from an observer near Venus. For example, Noon LST occurs on the day side of the planet, when the Observer- Venus-Sun angle is 0° and Midnight LST on the night side of the planet when the Observer-Venus-Sun angle is 180". LST is also used to describe the longitude of periapsis. Thus, when periapsis occurs at 6:00 pm LST, periapsis occurs over the evening terminator. Note that LST tied to the position of the observer, not to the physical surface of the planet or its rotation.

A number of characteristics of the reentry trajectory were determined by celestial mechanics. The reentry phase would begin in September 1992, at about midnight LST and progress toward the morning terminator. In late October an "S-Curve" would begin to loft the spacecraft to a higher altitude, reducing the atmospheric effects and the need for further maneuver, before the final reentry in mid December near noon LST. Throughout the month of September, altitude of periapsis dropped about 4 km/day duc to solar gravitational perturbations. The spacecraft would experience brief solar eclipse's (less than 30 minutes) and geocentric occultations at periapsis for most of tbc reentry phase. Finally, a season of long eclipse's (more than two hours) would begin in late December.

TRAJECTORY DESIGN

The dominant factor and source of greatest uncertainty in the trajectory design was tbc Venusian atmosphere. The average atmospheric density for reentry is best dcscribcd in the VIRA atmosphere model (Ref. 2). It is defined as a function of local solar time in 2 hour wide zones (30° of longitude). It is based on earlier PVO measurements at a different latitude and higher altitudes, and extrapolated to region of reentry. But the model cannot predict the specific density on a particular date. Daytime uncertainty is 10% and night time density is known to vary by as much as 50% (1σ) on a daily basis, particularly in the vicinity of the terminator. Since velocity change duc to atmospheric drag is directly proportional to density, trajectory prediction and design was inherently uncertain.

The two most important trajectory characteristics which could bc controlled were the maximum depth of penetration into the atmosphere before each maneuver and the time between those maneuvers. Choice of the maximum depth was dominated by thermal and communications constraints. Fiberglass components on the high gain antenna mast would begin to melt at 0.7 m/s of atmospheric drag. In addition, drag induces a displacement in the spin axis orientation, which could not bc permitted to move the Earth out of the narrow high gain antenna bcamwidth (60). It was known from the first 600 orbits that about 8° of spin axis displacement were imparted pcr m/s of drag induced velocity change.

The drag threshold also impacted a number of other critical factors. A slightly deeper drag pass would result in a slightly shorter orbital period, Since the PVO orbit period was nearly 24 hours, the cumulative effect was that the time of periapsis would advance earlier in the day, and actually walk around-the-clock in a fcw weeks time, which would put an extreme burden on the relatively small operation team. The time of periapsis and apoapsis (for science data acquisition and commanding, respectively) also determined the scheduling requirements for Deep Space Network (DSN) tracking antenna. Rut uncertainty in these times made long range scheduling difficult. It was also anticipated that late in the reentry phase, critical events might walk out of scheduled antcrrna tracking windows. Agreements were made with other projects to swap tracking time if needed.

A "Red Line" maximum velocity change of 0.7 m/s duc to atmospheric drag was established. The depth of penetration into the atmosphere was chosen such that if tbc maneuver could not bc performed as scheduled, there would be a contingency opportunity at the next apoapsis to maneuver before crossing the "Red Line" barrier. This trigger was generally between 0.2 and 0.4 m/s. The relatively low trigger values also made it likely that the time of periapsis would only walk around-the-clock once during the reentry.

The nominal mission plan called for periapsis raise maneuvers every 5th apoapsis. This fixed the size of the maneuvers to about 0.8 m/s with an altitude gain of approximately 20 km. This kept the periapsis altitude in the range of scientific interest (130 to 150 km) while giving the operations team a few days rest between each maneuver. A critical design feature was that in the event that a maneuver could not be preformed on schedule (either early or late), the next maneuver would still be performed on its nominal date. This forced a regularity onto the reentry design schedule despite the uncertainty of drag predictions, It would require 2.5 kg of propellant to perform nine maneuvers necessary to extend the mission beyond the "S-Curve". Fuel remaining on board was thought to be about 2.5 kg, with a 1007o uncertainty.

A nominal reentry trajectory was derived using the assumptions discussed above (Ref. 3). It was used for operations planning and scheduling of tracking passes. The altitude of periapsis for the nominal reentry trajectory is show in Fig. 2.

SPARSE TRACKING STRATEGY

The most difficult navigation challenge associated with supporting reentry was the possibility of short and infrequent tracking passes. This was a result of the extreme age of the spacecraft. After nearly fourteen years of operation, the solar cells had degraded. 10 meet spacecraft power requirements during each orbit, batteries were required to augment solar panel output. But the batteries themselves were also well beyond their life expectancy, and their ability to hold charge was decaying. So the spacecraft was operated by draining the batteries on each orbit for science, commanding and tracking. The bulk of each orbit was spent recharging the batteries. By early 1992 it was predicted that there might only be sufficient power for 4 hours of tracking per orbit.

The ability to meet project navigations requirements degrades as the amount of tracking data diminishes. Studies were preformed using PVO tracking data from 1980. At that time, there was abundant power on the spacecraft, and nearly continuous tracking was collected around the 24 hr orbit. In anticipation of the limited power situation during reentry, these studies determined how well period change could be measured using small amounts of data in short arcs distributed around the orbit. Variations were also made in the length of the arcs.

The results of the study arc summarized in Table 1. Here the degradation in the ability to determine period change is shown as a function of the placement and length of individual tracking passes. A baseline case, using all the data available, results in the best determination, with a normalized 1σ uncertainty of 1.0. The 1σ uncertainty in the period change for five other tracking scenarios is expressed relative to the baseline case.

It can be seen that prudent distribution of tracking about the orbit significantly mitigates against the degradation caused by the paucity of data, The amount of tracking is not as significant as where it is taken. A one hour pass at apoapsis is just as effective as a two hour pass. And four tracking pass around the orbit are much better than just three.

Further investigation of the placement of tracking passes revealed that the number of passes required pcr revolution could be substantially reduce by processing several consecutive orbits of data (Ref. 4). With this strategy, three consecutive orbits containing three periapsis passages would require only four tracking passes per revolution to obtain orbit determination accuracy comparable to continuous coverage. The four tracking passes would be 15 to 30 minutes in length ant] placed at periapsis, apoapsis, and roughly geometrically in between at plus and minus 4 hours from periapsis. In practice, no tracking could be obtained at periapsis duc to geocentric occultation, so the periapsis pass was divided into two brief passes approximately one hour before and after periapsis.

During the entry phase, navigation is required for support of propulsive maneuvers ant] entry science. Of particular interest to science is the determination of the velocity change imparted to the spacecraft while in the Venus atmosphere. This velocity change may be related to the drag experienced by the spacecraft and hence the atmospheric density. During the previous PVO operation in the atmosphere from 1978 to 1980, the procedure for determining the velocity change involved fitting one revolution of data, starting at periapsis. Then the difference between the osculating orbit periods of successive orbits, with and without drag would yield the period change, which could be easily be related to the velocity change. No period change could be determined for orbits in which maneuvers were performed to push periapsis back down into the atmosphere.

The above procedure would not be viable for the 1992 reentry, because of the paucity of tracking data. For reentry, the atmospheric drag was modeled as a small retro propulsive maneuver in a direction opposite to the velocity vector at periapsis. The length of the burn was taken to be 100 seconds, which is approximately the length of time that the spacecraft was in the atmosphere. The sparse data strategy estimates the velocity change directly, instead of determining the period change and then calculating the velocity change. The periapsis raise maneuvers can be estimated in the sparse technique, so no drag measurements are lost. Finally, the three revolution fit increases the amount of rotation in the orientation of the orbit plane with respect to the line-of-sight (I_{pos}). 'I'his helps reduce the well known uncertainty in angular orbital parameters when I_{pos} is near 90° in mid-September 1992 (Ref. 5).

The associated orbit period change (ΔP) from the old technique can be computed from the partial derivative of period with respect to velocity and is given by

$$\Delta P = \frac{\partial P}{\partial v_p} \Delta V$$

$$\frac{\partial P}{\partial v_p} = 6\pi \frac{v_p a^{\frac{5}{2}}}{\mu^{\frac{3}{2}}}$$

$$a = \frac{-\}1}{h}$$

$$h = v_p^2 - \frac{2\mu}{r_p}$$

where ΔV is the velocity change, v_p is the velocity at periapsis, r_p is the radius of periapsis and μ is the Venus gravitational constant.

ORBIT DETERMINATION

Estimation of Drag

The estimation of drag from radiometric tracking data involves separating the velocity imparted to the spacecraft associated with atmospheric drag from the velocity imparted by all other sources including both gravitational and nongravitational accelerations. The significant other sources include the Venus gravity harmonics, solar tide, solar radiation pressure, and any spacecraft propulsive or attitude maneuvers. over a relatively short data arc, the solar gravitational perturbations and nongravitational accelerations arc predictable and do not contribute significantly to the drag estimate error. Unmodelled non-uniformity in the Venus gravity field, on the other hand, result in a large perturbation of the orbit that reaches a maximum near periapsis just where the drag acceleration attains a maximum. Thus, the main orbit determination problem is separating the gravity perturbation from the drag perturbation.

In order to gain some insight into the problem of drag estimation it is useful to examine the response of the tracking data to error in the values of key parameters involved in the estimation process. The two key parameter sets arc drag and unmodelled gravity harmonics errors. The drag is described by the atmospheric density. The gravity field harmonic truncation error is approximated by the sum of the perturbations caused by the gravity harmonics, in this case above degree 21. The representation of the gravity field truncation error by the highest degree harmonics available is somewhat arbitrary. Since the degree 22 harmonics have been omitted from the solution, we may expect that the error in these harmonics may be as high as 100% of their nominal values, For the Venus gravity field, it appears that the truncation error is bounded by the highest degree harmonics included in the fit, or the degree 21 harmonics, since these approximate in some sense the harmonics that have been excluded.

The data residual signatures of atmospheric drag and gravity harmonics are shown in Fig. 3. 'The orbit deter mination filter effectively looks at these two curves and separates one from another based on the characteristic response or signature of the parameter. If wc restrict the orbit determination solution to one hour of data centered on periapsis in Fig. 3, the filter will not be able to determine the drag since the perturbation of the spacecraft is dominated by gravity harmonics in this region. However, the gravity harmonics conserve energy around the orbit and their signature is periodic whereas the atmospheric drag reduces the orbital energy resulting in a signature that grows with time. An hour or so of tracking data after periapsis reveals a secular growth in the atmospheric drag signature that may be easily separated from the gravity harmonics signature by the filter.

Orbit Determination Strategy

The basic orbit determination strategy was to use a sliding window of three orbit fits, with an integration epoch slightly before apoapsis. The force model employed newtonian gravitational accelerations for the sun and planets, plus relativistic gravitational accelerations for the sun and Jupiter. Oblateness for Venus used the 21x21 harmonic field VGM6A (derived from 1970 to 1980 PVO and 1990 Magellan tracking). Solar pressure was modeled as a spacecraft bus and a parabolic, Earth pointing antenna. Atmospheric drag at each of the three periapsis passages was modeled as a 100 second finite maneuver, centered at periapsis, directed opposite the velocity vector. Consequently, no atmospheric model was used. Spacecraft maneuvers (periapsis raise, re–orientation and spin aligrlment/period adjustments) were modeled as finite burns.

Estimated parameters included the spacecraft state, atmospheric drag (as finite velocity changes) and maneuvers as needed. Solar pressure effects were not estimated, as they were well determined after nearl y 14 years of operations. A priori sigma's for the state were essentially infinite, and for maneuver 10% of the anticipated thrust level and 1° for right ascension and declination of thrust pointing. A priori sigma's for the drag maneuvers were set from 5 to 10 times greater than the value anticipated from the VIRA model. A priori values for the drag maneuver were set at one order of magnitude less than the VIRA prediction.

Errors due to gravity mismodelling, station locations, transmission media calibrations, and planetary ephemerides were not dealt with due to operational considerations. Consequently, formal statistics give an optimistic measure of the actual orbit determination accuracy. From examination of residual orbit–to–orbit changes in the orbital elements, a more realistic assessment of orbit uncertainty has been made. This assessment suggests that the actual statistics for period change differ from the formal statistics, where a realistic "reported" sigma is the root sum of squares of the formal sigma and 20 msec.

Two way conventional Doppler tracking were employed at S-band frequency. Doppler count times of 10 seconds were used near periapsis and 60 seconds for the rest of the orbit. Tracking data 80 minutes on either side of periapsis was deleted to reduce gravity mismodeling. Doppler data were weighted at the observed data noise level (generally 1 rnm/see).

Each day, the window was advanced one orbit. No a priori covariance information was used from the previous fit, but orbital elements and drag ΔV estimates were examined for consistency.

MISSION OPERATION STRATEGY

The basic operational strategy called for a periapsis raise maneuver every fifth orbit, with contingency opportunities at the previous and following apoapsis. Radiometric tracking data was scheduled to be collected at apoapsis, before and after periapsis, and 4 hours before and after periapsis. Navigation deliveries were tied to the time of periapsis. Orbit determination would be preformed immediately after the periapsis plus 4 hour pass. A "quick look" estimate of the drag experienced at the previous periapsis and a prediction of the drag level and time for the next periapsis would be delivered about two hours later. On orbits with deep drag passes this information would be used to determine if a periapsis raise maneuver was necessary at the next apoapsis. This left about 6 hours for the operation team to prepare and uplink the maneuver command sequence.

After the "quick look" estimate, a second, definitive science solution would be performed, using data Up to apoapsis. This solution would be used for sequence planning, science data analysis, atmosphere modeling and telecommunications predicts generation.

Navigation functional requirements in support of project operations included 1) determine velocity change due to drag at the last periapsis, 2) predict the time of the next periapsis, 3) predict the velocity change from drag at the next periapsis, and 4) deliver in time for apoapsis maneuver design. Navigation functional requirements in support of science included 1) provide period change duc to drag for OAD, and 2) analyze updated OAD atmosphere models. The specific navigation numerical requirements were 1) determine periapsis altitude to 250 m, 2) determine atmospheric drag commensurate with spacecraft survival needs, 3) determine period change duc to drag to 0.1 sec for science analysis, and 4) predict the time of the next periapsis to within 30 scc.

POST SUPERIOR CONJUNCTION RESULTS

The first opportunity to test the ncw procedures with real data occurred after the spacecraft emerged from Superior Conjunction in July 1992. Periapsis altitude was essentially constant at 205 km because the spacecraft had entered an "S-Curve" phase of its trajectory. The spacecraft was crossing the evening terminator, going from a regime of relatively high to low drag. The drag would remain low until the trajectory began it final decay. At this time, a short window occurred in which the spacecraft would experience significant drag. It was possible to test the new navigation procedures and calibrate the on-board neutral mass spectrometer (ONMS) before reentry data acquisition began.

Following several maneuvers to correct orientation and spin rate, there were 21 days of maneuver free tracking to test the sparse tracking data procedure. unfortunately, the Sun-Earth-Probe angle over this period varied between only 3.4° and 9.8°. Consequently, the data noise and formal drag measurement uncertainties were extremely high and it was difficult to determine if the procedure was working as expected. The measured drag, expressed as both a velocity and period change, is presented in Table 2, along with formal onc sigma uncertainties, as well as a '(reported" sigma for period change. Orbital elements between successive fits were in good agreement, but the drag measurements for the first and third periapsis maneuver were not consistent. One way to validate the solutions was to compare the measured drag for the middle periapsis against the predicted drag' from an existing atmosphere model. This is show in Fig. 4, using the VIRA 6:00 pm and 7:00 pm models. It is not at all obvious if the measured results arc in agreement with the model. The interpretation is complicated by the fact that the VIRA model is based on data collected near solar maximum and the 6:00 symmetric model is colder than the actual 6:00 pm atmosphere. In addition, the VIRA measurements were made at 150 km, so the atmosphere model is extrapolated up the this altitude. This shows the inherent weakness in using discrete hourly atmosphere models. An alternate approach is to interpolate the logarithms of the discrete hourly values. This was suggested by Keating, because it accounts for the exponential natu re of the atmosphere than a linear interpolation. This result is shown in Fig. 5. In this case, it is obvious that the drag measurements are close to the model prediction. The difference in slope of the two curves indicates that the navigation measured atmosphere is warmer than the model, which is a consequence of the VIRA formulation. Keating has shown that after correcting for solar activity and using a non- symmetric atmosphere, the measurements agree to within 5% of the VIRA predictions (Ref. 6).

These results demonstrate that the new drag estimation technique performed as predicted. What is more significant is that the technique was able to measure atmospheric density one order of magnitude lower than had previously been achieved by PVO. This greatly extends the altitude range over which direct atmospheric density profiles can be determined. One other surprise at this point was that the batteries were performing much better than expected. As a result, between 4 and 6 hours of tracking data was collected each orbit. Navigation 'tracking was severely curtailed in July and early August, due to damage to the 70 m Goldstone tracking antenna caused by the magnitude 7.1 Landers earthquake.

REENTRY OPERATION AND RESULTS

Navigation

The reentry operation began on September 2, 1992, at an altitude of 155.5 km, when the spacecraft experienced atmospheric drag in excess of 1 mm/sec. Daily "quick look" and science solutions were delivered as scheduled. Despite dire predictions, both the solar panels and batteries performed much better than expected, About seven hours of tracking data were available for each three rev solution, almost twice what was expected! Data noise was generally between 1 and 2 mm/see. A typical plot of post fit residuals is shown in Fig. 6. Of particular interest are the trends and biases of about $\frac{1}{4}$ to $\frac{1}{2}$ mm/see exhibited in the data, which arc due to gravity mismodeling. These biases could be eliminated by removing more data near periapsis, or deleting the entire periapsis track, but the orbit–to-orbit consistency of inclination degraded severely. Even though these biases were an indication that some gravity field mismodeling was present, removing them had little effect on the estimates of the operationally critical parameters drag, altitude of periapsis or period (semi-major axis). Despite this known, albeit small error, operational navigation accuracy and solution delivery requirements were easily met.

The measured drag for the entire reentry, expressed as both a velocity and period change, is presented in Table 3, along with formal one sigma uncertainties, as well as a '(reported" sigma for period change. When drag was in excess of 0.1 m/s, onboard measurements of the displacement of the spacecraft spin orientation was used to make an independent estimate of induced drag. 'I'his estimate, with a precision of about 1 cnl/see, was consistent with the navigation derived drag measurements.

The first maneuver occurred on September 8, 1992 (Labor Day Holiday!), at an altitude of 134.9 km, after a drag velocity change of 0.153 m/s. Fitting through maneuvers did not degrade the navigation estimates of critical operational parameters.

Operations

The maneuver decision was based on navigation solutions, backed up by spacecraft re -orientation measurement. Data from the ONMS was typically not available in time for consideration in maneuver planning. Maneuvers generally occurred on the scheduled dates, because the altitude of periapsis was "controlled by solar gravitation] perturbations, not the atmosphere or drag effects. After each maneuver, a new reference trajectory was generated for mission planning purposes and for DSN frequency predicts.

It became evident that the "quick look" drag measurement was not the mission operations driver anticipated during reentry planning. Spacecraft sequencing required the time of periapsis be known to within 30 sec. For deep penetration orbits with high drag, trajectory predictions beyond one day could not meet the 30 sec requirement due to the variability of the atmospheric density. Spacecraft sequences for high passes with low drag, were generated during the previous saw–tooth. Consequently, the prediction of time of periapsis was corrupted by the deep drag pass immediately before the periapsis raise maneuver. It took two full orbits of post maneuver data to reestablish the time of periapsis prediction. But by that time, the spacecraft was again entering the high drag regime, and the time of periapsis could only predicted ahead onc orbit with sufficient accuracy for scheduling spacecraft activities. Consequently, the critical navigation activity changed from predicting if a maneuver was necessary, to predicting the time of periapsis of the next orbit for sequence generation. As a result, the periapsis plus 4 hr critical delivery was moved to apoapsis. The delay in delivery caused the "quick look" solution to span the same data set as the science solution (three orbits, apoapsis to apoapsis). This resulted in a single unified deliverable, greatly reducing the amount of work necessary to meet project requirements. The time of periapsis prediction was accurate to +/- 20 msec.

Atmosphere

By the end of the second maneuver, a definite pattern of atmospheric behavior had been established. The measured atmospheric density was consistently skewed away from the VI RA model prediction. In particular, the "real" atmospheric density was lower than predicted by VIRA at the top of the reentry corridor, and higher than predicted at the bottom of the corridor. A plot of the navigation drag observations and the VIRA predictions is shown in Fig. 7. The bias in the atmosphere is more readily seen in a plot of the percentage difference between the navigation observations and the VIRA predictions, as shown in Fig, 8. Keating suggested that for prediction purposes, a navigation model, composed of the logarithmic interpolation of the VIRA midnight and noon models would be a good approximation. A plot of the percentage difference between the navigation observations and the navigation model predictions is shown in Fig. 9. Although the empirical navigation model is inconsistent with physical atmospheric conditions, it did provide a better predictions of drag and the time of periapsis at low altitudes.

The higher than anticipated drag at low altitude increased the spacecraft risk before each periapsis raise maneuver, But consistently early maneuvers would degrade the science return and upset the mission schedule. A plan was implemented in which small spin trim maneuvers were performed onc orbit before the scheduled periapsis raise maneuver and resulted in a 500 m altitude raise before the deep atmosphere passage. This small biasing was sufficient to prevent periapsis raise maneuvers from being triggered early.

Reentry

Early indications were that there would be sufficient fuel left to reach the "S-Curve" occurring in October and the morning terminator passage. But, the 6th periapsis raise maneuver only achieved 80% of its intended altitude gain. Several attempts were made to reboost the spacecraft, but telemetry indicated that fuel was finally exhausted in the thruster used to raise periapsis. As the spacecraft penetrated deeper into the atmosphere, its was spun up so its attitude would be less deflected by the high drag, and communications with Earth maintained. The faster spin rate forced a small amount of residual fuel into the periapsis thruster, and one final maneuver was performed, resulting in a 400 m altitude gain. On Oct. 8, 1992, PVO began its 5056th orbit of Venus. The periapsis occurred at an altitude of 128.5 km and the anticipated drag in excess of 2 m/s. Following periapsis, no radio signal was detected from either the high or low gain antenna, and attempts to establish contact over the next day failed. It is thought that contact was lost due to electronic component failure from excessive heating. The spacecraft continued to orbit for some unknown period of time before crashing into the planet.

CONCLUSION

Pioneer 12 successfully performed atmospheric reentry at Venus in the September 1992. PVO navigation overcame a number of adverse conditions by developing innovative techniques for meeting project requirements. These include a tracking strategy for which orbit determination accuracy was optimized for sparse tracking data coverage. The technique also allowed measurement of atmospheric drag a full order of magnitude lower than had previously been achieved at Venus. This mission marked the first usc of logarithmically interpolated atmospheric models at Venus for long range trajectory prediction. The PVO navigation team was able to adapt its operation to successfully meet changing requirements driven by the dynamic atmosphere and evolving physical condition of the spacecraft.

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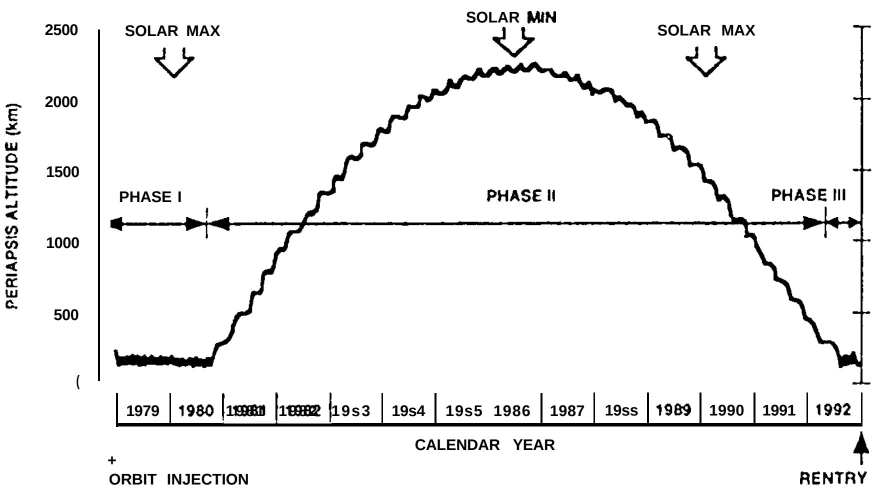

Figure 1 : **Long Term** Evolution of Altitude of **Periapsis**

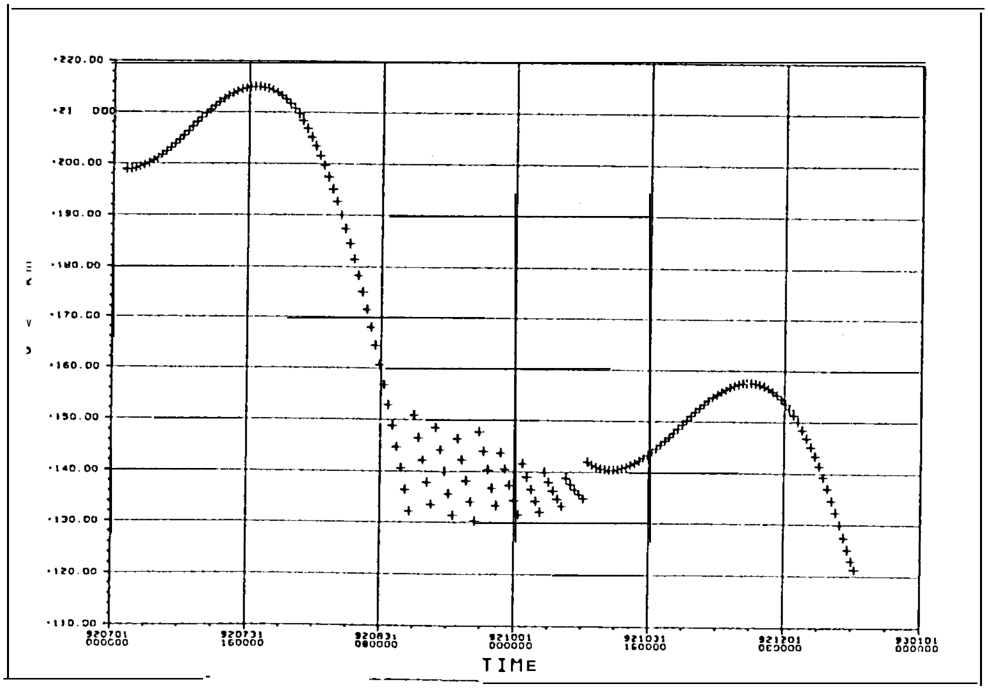

Figure 2 : Altitude of **Periapsis** for Nominal Reentry **Design**

Case	Hours of Data and Location				σ
	Peri	Apoa	Peri–4	Peri+4	
1	Use All Data				1.0*
2	2.0	2.0	0.0	0.0	6.0
3	2.0	2.0	0.0	1.0	3.4
4	2.0	2.0	1.0	1.0	1.4
5	2.0	1.0	0.5	0.5	1.6

* (normalized 1σ)

Table 1: Relative Uncertainty of Period Change as a Function of Tracking Data Amount and Location

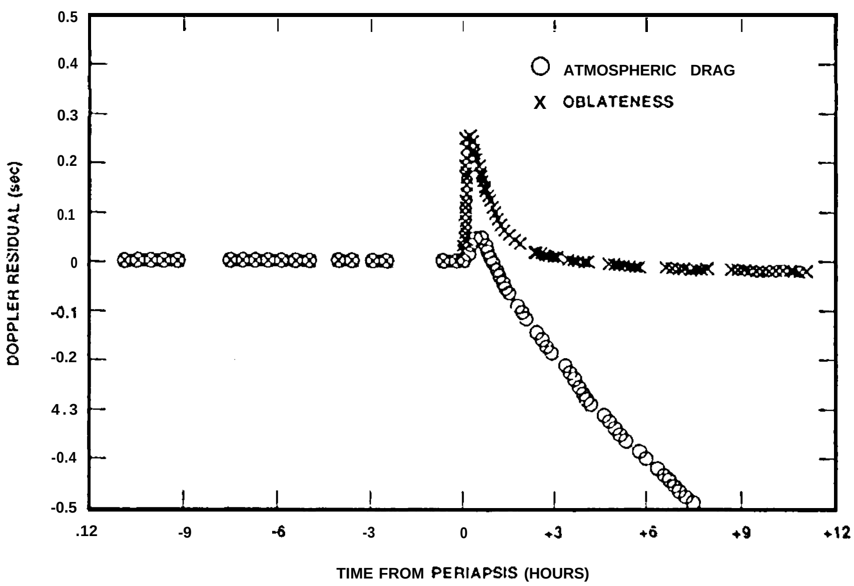

Figure 3 : Residual Signature Due to Drag and Gravity Harmonics

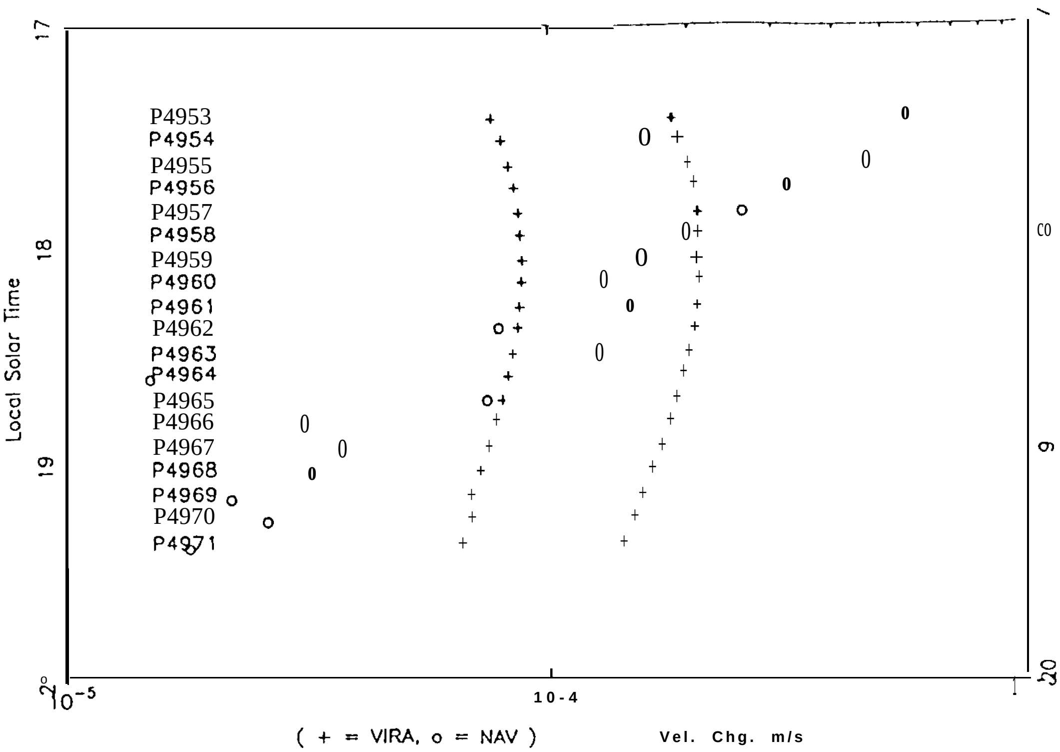

Figure 4 : Measured Velocity Change vs. VIRA 6:00pm and 7:00pm Hourly Models

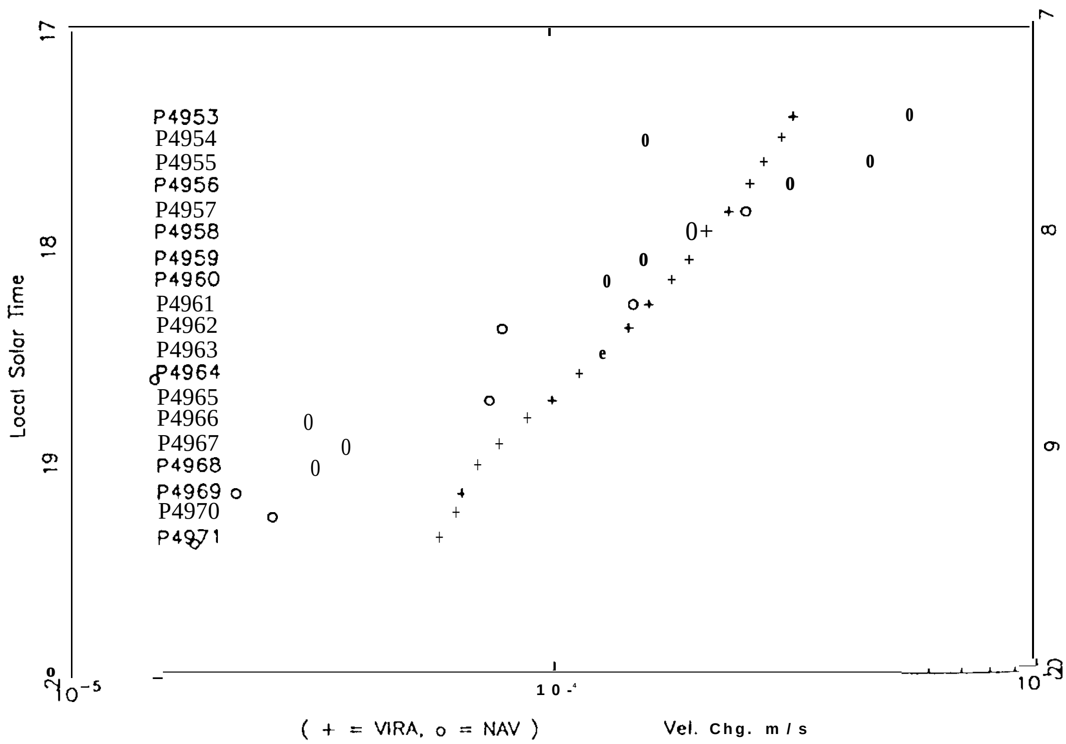

Figure 5: Measured Velocity Change vs. VIRA Interpolated Model

Orbit #	AV mm/see	Formal u mm/see	A P sec	Forma] u sec	Reprtd σ sec
4954	*0.159*	*0.048*	*0.049*	0.015	0.025
4955	0.467	0.016	0.144	0.005	0.021
4956	0.321	0.025	0.099	0.008	0.022
4957	0.260	0.026	0.080	0.008	0.022
4958	0.198	0.199	0.061	0.061	0.064
4959	0.156	0.444	0.048	0.137	0.138
4960	0.131	0.114	0.040	0.035	0.040
4961	0.149	0.284	0.046	0.087	0.089
4962	0.079	0.292	0,024	0.090	0.092
4963	0.128	0.294	0.039	0.091	0.093
4964	0.015	0.011	0.005	0.003	0.036
4965	0.075	0.006	0.023	0.002	0.028
4966	0.031	0.007	0.010	0.002	0.028
4967	0.037	0.005	0.011	0.002	0.028
4968	0.032	0.005	0.010	0.002	0.028
4969	0.022	0.002	0.007	0.001	0.022
4970	0.026	0.004	0.008	0.001	0.022
4971	0.018	0.004	0.006	0.001	0.022

Table 2: Atmosphere Induced Drag Expressed as Velocity and Period Change

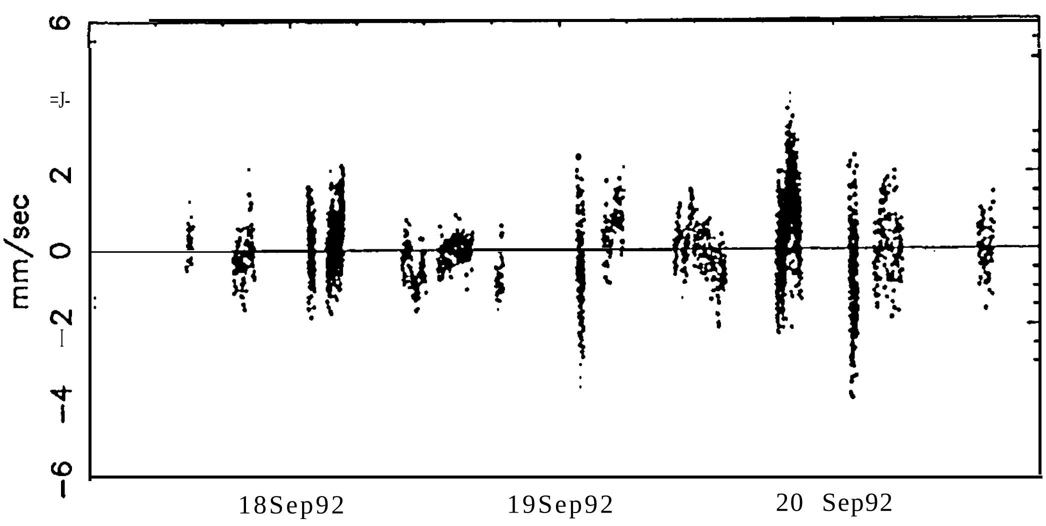

Figure 6 : Typical Pioneer 12 Doppler Residuals

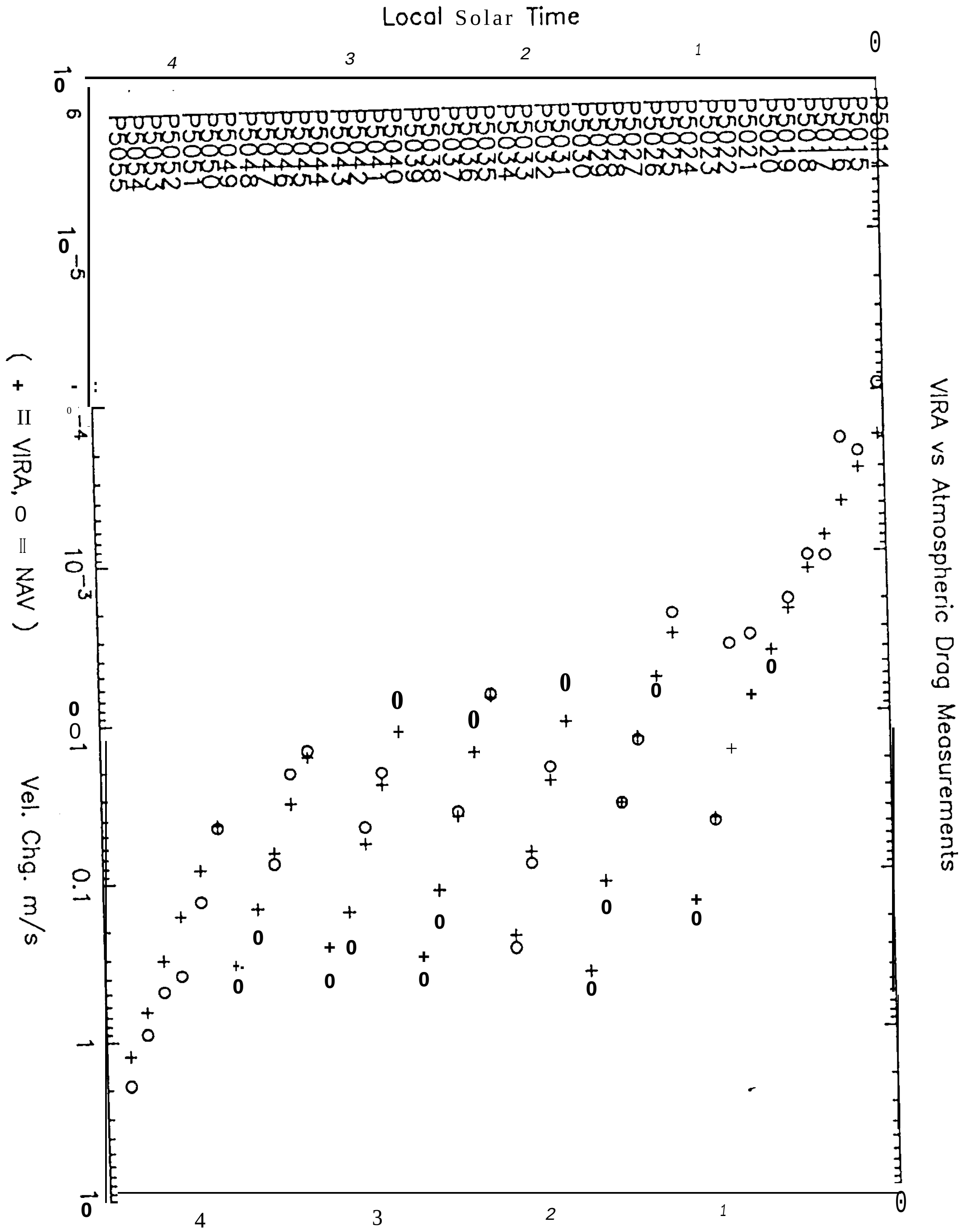

Figure 7 : Measured Velocity Change vs. VIRA Interpolated Model for Reentry

Orbit #	ΔV mm/sec	Formal σ mm/sec	Δ P sec	Formal sec	σ Reprtd CT sec
5014	0.091	0.003	0.028	0.001	0.020
5015	0.239	0.006	0.074	0.002	0.020
5016	0.197	0.011	0.061	0.004	0.020
5017	1.059	0.008	0.327	0.003	0.020
5018	1.041	0.010	0.322	0.003	0.020
5019	1.964	0.005	0.607	0.001	0.020
5020	5.402	0.005	1.670	0.001	0.020
5021	3.252	0.011	1.006	0.004	0.020
5022	3.704	0.007	1.146	0.002	0.020
5023		0.004	14.739	0.001	0.020
5024	202.285	0.038	62.565	0.012	0.023
5025	2.336	0.037	0.722	0.011	0.023
5026	7.246	0.006	2.238	0.002	0.020
5027	14.444	0.005	4.464	0.002	0.020
5028	36.267	0.005	11.210	0.002	0.020
5029	164.957	0.005	50.977	0.001	0.020
5030	542.047	0.040	67.210	0.012	0.023
5031	6.305	0.018	1.941	0.005	0.021
5032	20.864	0.005	6.424	0.002	0.020
5033	84.162	0.005	25.913	0.002	0.020
5034	284.947	0.035	87.667	0.011	0.023
5035	6.781	0.025	2.083	0.008	0.021
5036	10.539	0.004	3.239	0.001	0.020
5037	38.825	0.007	11.933	0.002	0.020
5038	192.254	0.014	59.070	0.004	0.020
5039	440.258	0.019	135.057	0.006	0.021
5040	7.676	0.013	2.350	0.004	0.020
5041	21.500	0.003	6.585	0.001	0.020
5042	47.163	0.004	14.446	0.001	0.020
5043	269.197	0.014	82.403	0.004	0.020
5044	434.701	0.016	132.815	0.005	0.021
5045	13.881	0.023	4,233	0.007	0.021
5046	21.557	0.003	6.575	0.001	0.020
5047	77.926	0.003	23.769	0.001	0.020
5048	226.722	0.006	69.110	0.002	0.020
5049	458.198	0.042	139.418	0.013	0.024
5050	45.733	0.021	13.890	0.006	0.021
5051	132.048	0.013	40.095	0.004	0.020
5052	385.840	0.007	[illegible]	0.002	0.020
5053	488.316	0.007	147.718	0.002	0.020
5054	903.273	0.010	272.161	0.003	0.020
5055	1901.751	0.019	568.316	0.006	0.021

Table 3: **Atmosphere Induced Drag** Expressed as Velocity and Period **Change**

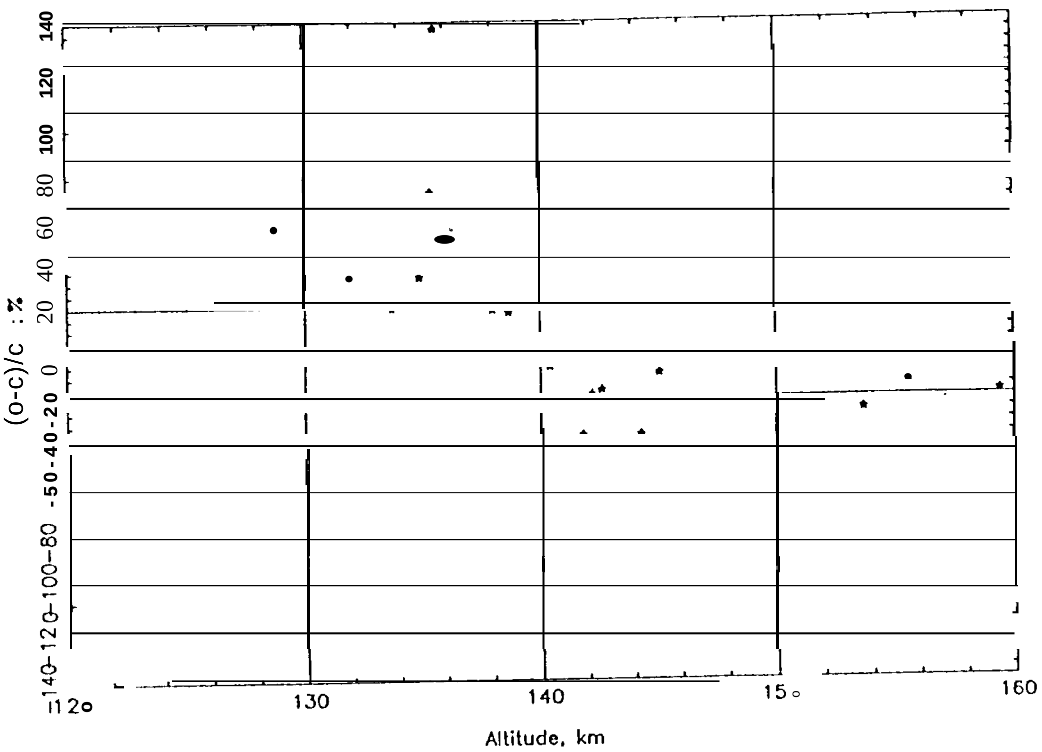

Figure 8 : Percentage Difference Between Measured Velocity Change and VIRA

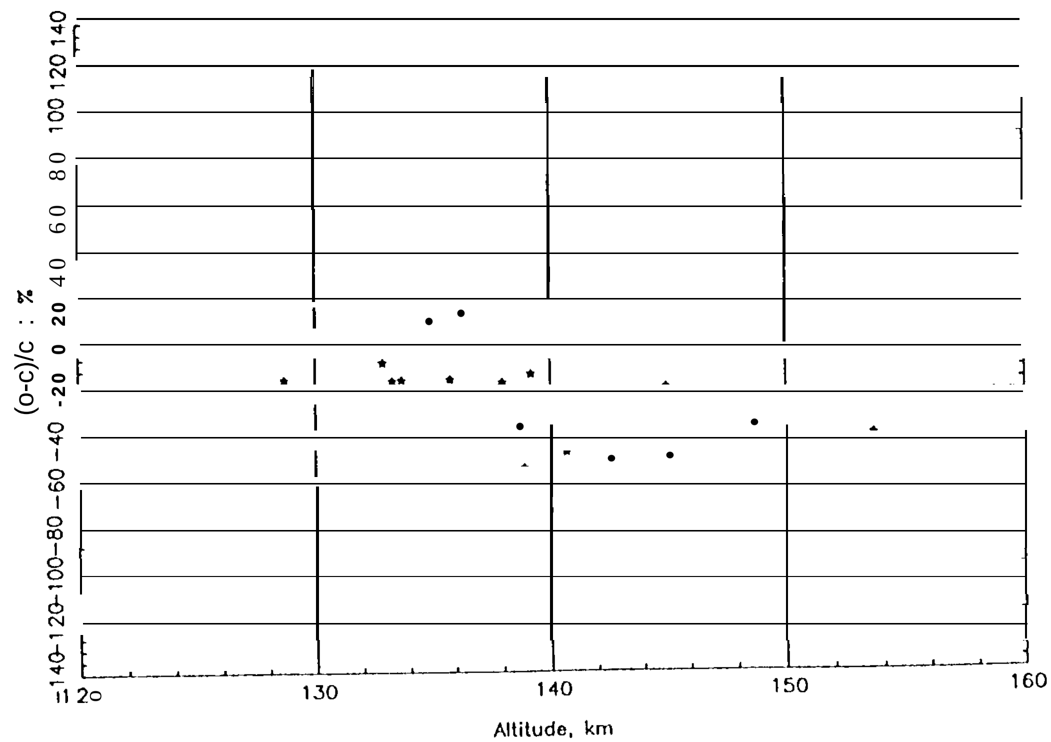

Figure 9 : Percentage Difference Between Measured Velocity Change and Nav Model

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Mvr #	Orbit #	Alt Peri km	ΔV mm/sec	LST hh:mm
1	5024	134.9	202.285	01:07
2	5030	132.1	542.047	01:45
3	5034	133.8	284.947	02:10
4	5039	132.9	440.258	02:42
5	5044	133.5	434.701	03:14
6	5049	132.9	458.198	03:45
N/A*	5055	128.8	1901.751	04:23

* (spacecraft lost)

Table 4: Periapsis Raise Maneuvers